An Example of Crosswell Data Showing Frequency Side-Lobes due to Permeability

Enclosed is an example showing a part of the cross-well seismic data-set that was recorded with the seismic downhole source in one well and the seismic downhole receiver in the other well. This data represents the frequency spectrum of the received signals in the receiver well. The distance between the two wells is 990 feet. The subsurface formations were deposited in stable geologic conditions. The dip of the formations based on the well logs is about 1 degree. The depths of the downhole source and downhole receiver during the recordings were maintained so that both the source and receiver were in the same subsurface geologic formation. The source transmitted a mono-frequency signal of 1,000 Hz. The crosswell data were recorded at 10-foot depth intervals. The recorded data were analyzed using Fast Fourier Transform (FFT). The Lower Austin Chalk at the survey location has porosity above 15% and is continuous between the two wells. The behavior of the producing wells in the region indicates that the Lower Austin Chalk has a certain amount of permeability, since the wells start producing water after the oil production is depleted.

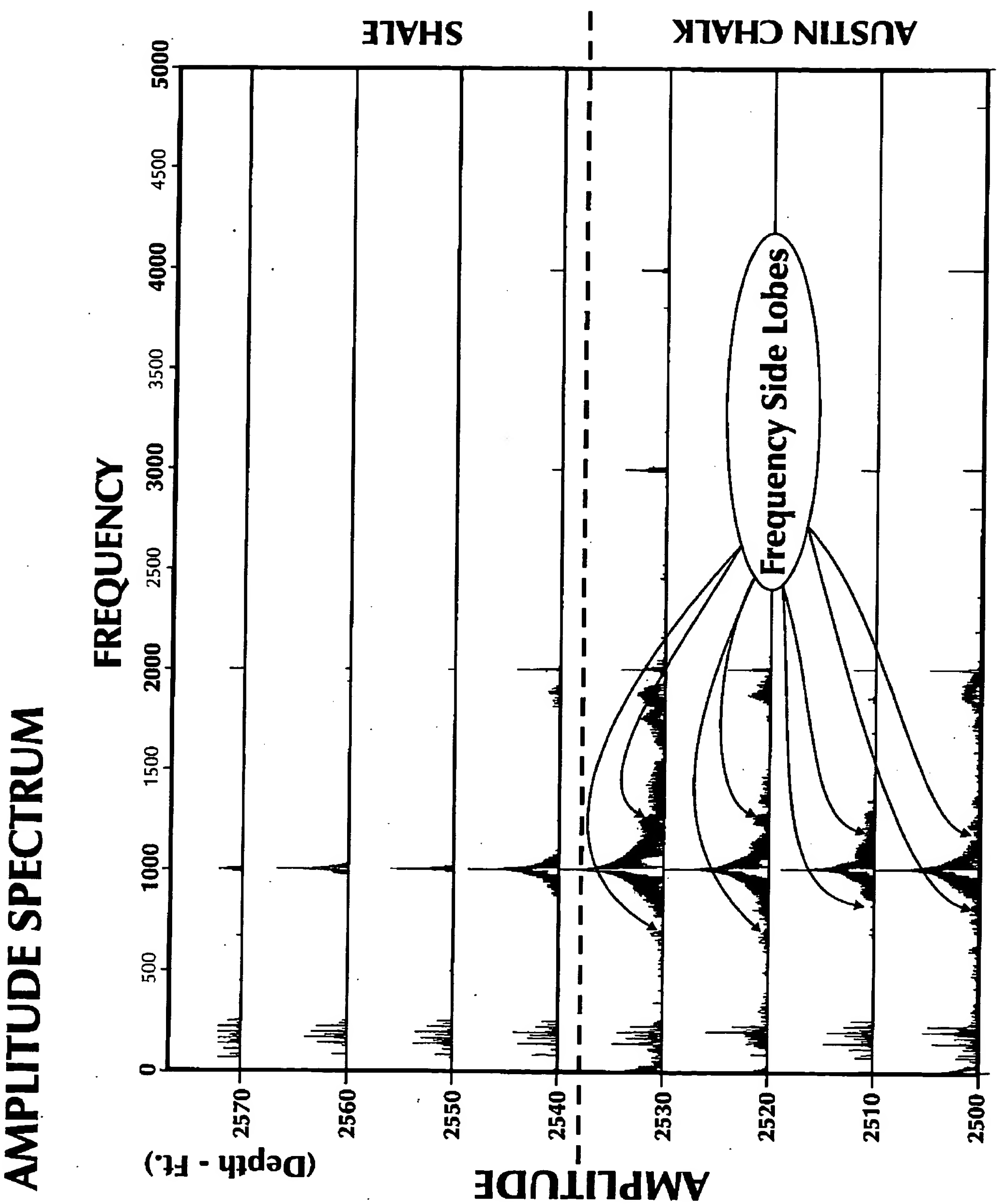
The frequency spectrum of the crosswell data, which were recorded using 1,000 Hz frequency transmitted by the source, indicates that there is higher elastic nonlinearity in the lower 30 feet of the Austin Chalk which overlies the Eagleford Shale. The elastic nonlinearity of the rocks in the inter-well space is indicated by the relative amplitude levels of the harmonics (2,000 Hz, 3,000 Hz, and 4,000 Hz) in the frequency spectrum plot of the crosswell data. The density/porosity logs also show that the lower 30 feet of

the chalk has the highest porosity, which is above 15%. Theoretical work by Donskoy, McKee, et al (1997), has established a relationship between elastic nonlinearity of the rock and its porosity. Their studies show that when a seismic wave propagates through a nonlinear rock, the elastic nonlinearity of the rock can be measured by the relative amplitudes of the harmonics generated.

The other very noticeable and interesting phenomenon is that there are frequency side-lobes of the transmitted frequency, which are present in the data transmitted through the Lower Austin Chalk. The frequency side-lobes are not present in the Upper Austin Chalk, Eagleford Shale and Del Rio Clay. These side-lobes are generated due to the nonlinear interaction between the compressional wave and the 'Drag-wave' or 'Slow-wave', as described in the Patent Application No. 09/853,190. The highest permeability between the source and receiver well is indicated by the relative amplitude of the side lobes at the depth of 2,530 feet. The boundary of the Austin Chalk and Eagleford Shale is between 2,530 and 2,540 feet. The depths are measured from the surface.

There is a great deal of lateral heterogeneity in the Austin Chalk. Due to this lateral heterogeneity, the permeability across the two wells, which are 990 feet apart, is expected to change laterally. The higher and lower permeability will exist in patches. For this reason the side-lobes created due to the nonlinear interaction between the 1,000 Hz. compressional wave and the 'Drag-Wave' will show smearing of the frequencies. The smearing is caused due to lateral variations in the 'Drag-Wave' velocity across the 990 feet distance. In well-sorted sandstones, where the permeability and porosity will have

more lateral uniformity and consistency, the frequency side-lobes will be better defined. This example shows the usefulness of the method described in the Application, since the presence of the side-lobes in the crosswell data are an 'indicator' of the permeability connection between the two wells at specific and known source/receiver depths. The frequency of the side-lobes can be used to calculate the 'Drag-Wave' velocity, from which bulk 'tortuosity' of the formation connected between the two wells can be calculated. Once the bulk 'tortuosity' is known, the bulk permeability can be estimated. At present there is no known seismic method of mapping bulk tortuosity or bulk permeability of the rock formations between any two wells.


AMPLITUDE SPECTRUM
FREQUENCY
AMPLITUDE
(Depth - Ft.)
SHALE
AUSTIN CHALK
Frequency Side Lobes
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2570
2560
2550
2540
2530
2520
2510
2500